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Bio-Inspired Control of Civil Infrastructure

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Structural Control of Civil Infrastructure Using Bio-Inspired Wireless Sensor Nodes

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Abstract

Civil infrastructure is constantly at risk for failure due to unpredictable high impact loadings, including earthquakes and high winds. Over the course of the last decade, a bio-inspired wireless sensor node has been developed for the purpose of structural monitoring and control. This node functions similar to the mammalian cochlea found in the inner ear and benefits include its high data compression capabilities. In this study, a bio-inspired control algorithm was applied to a single story structure subject to base excitation in order to produce more effective methods of control. The effect of the control law on the response of the structure was assessed in simulation using various performance metrics. It was determined that the response of the system could be effectively reduced using the bio-inspired algorithm, as well as an active mass damper. The study was able to effectively illustrate that the displacement was reduced by a normalized value of 0.68 from the uncontrolled to the controlled case.

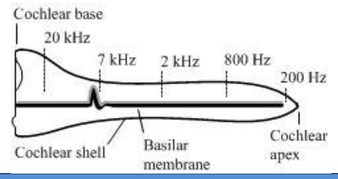
Inspiration for the Bio-Inspired Wireless Sensor

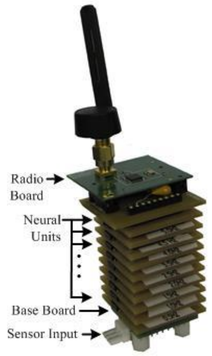
Traditional actuation systems within current civil infrastructures typically consist of multiple controllers and actuators. The sensor networks that implement control in these system, however are not capable of effective global decision-making due to delays in the system as a result of required data processing and communication time.

The bio-inspired node draws inspiration from the cochlea of the human ear, with each neuron board serving as a bandpass filter in which various frequencies are recorded by the sensor and sent wirelessly as "packets." Benefits of the sensor include:

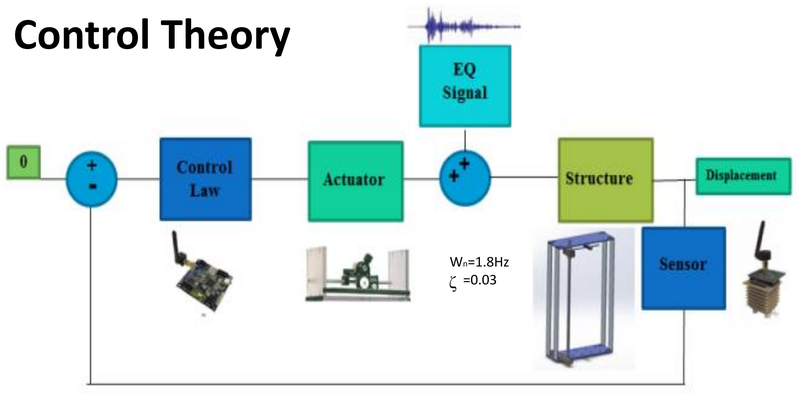
1.) Real-time decomposition of a time based signal
2.) High speed data processing
3.) Data compression

With these traits, the bio-inspired sensor node should be able to implement real-time localized control within civil infrastructure.



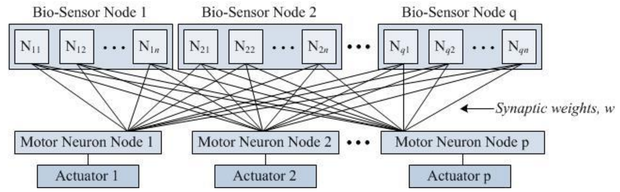


Control Theory



Bio-Inspired Control Theory

In most biological systems, muscle actuation relies on data transmission and information integration within sensory neurons. Information is sent to motor neurons through layers of neurons in which the synaptic strength of the nerves amplify the signal. This allows for multiple signals to be sent simultaneously to these motor neurons which then dictate muscle actuation.



This method of communication and actuation within the neurological network is integrated into the wireless sensor network using the relationship

$$F_k = \sum w_{ijk} N_{ij} \qquad \text{Eq. 1}$$

in which w_{ijk} is the synaptic strength , j^{th} is the neural unit on the i^{th} sensing node, F is the control force for the k^{th} motor neuron node, and N_{ij} is the detected peak value of the original signal received by the bio-inspired node.

Determining System Parameters

A single tory shear structure's response was modeled using the traditional second order equation of motion of base excitation:

$$\boldsymbol{M\ddot{x} + C\dot{x} + Kx = Fu} \qquad \text{Eq.1}$$

in which M is the mass, C is the damping coefficient, K is the stiffness, H is the external excitation, F is the control force, and u is the voltage applied to the motor that implements the control.

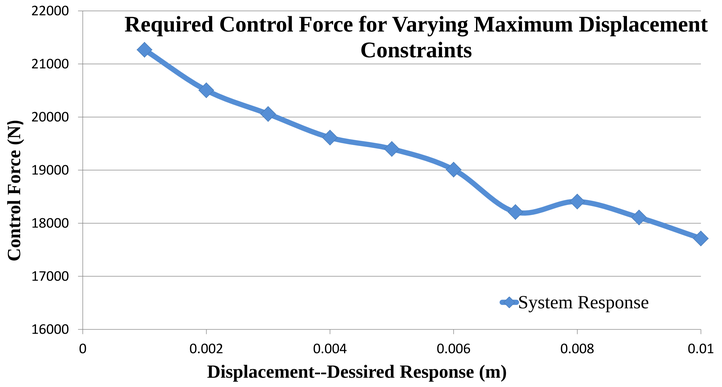
The weighting values used in the bio-inspired control algorithm were derived using the Linear Quadratic Regular (LQR). Coefficients were developed by minimizing the performance index, J (Eq.2), for a given control matrix, R (Eq. 3), and state matrix, Q:

$$J = \int_0^\infty (\boldsymbol{x^T Q x} + Ru^2)\mathrm{dt} \qquad \text{Eq.2}$$

$$R = \frac{1}{(\max desired\ control\ force^2)} \qquad \text{Eq. 3}$$

$$Q = \frac{1}{(\max desired\ system\ displacement^2)} \qquad \text{Eq.4}$$

To optimize the effectiveness of the control algorithm, the idealized maximum desired response was varied and the K matrix that resulted in the minimized structure displacement was obtained.



Simulation Results

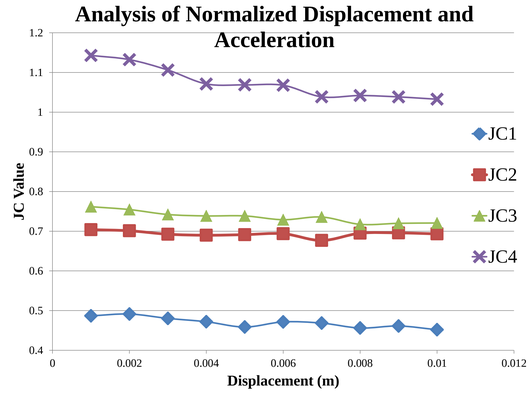
Simulations were run in order to test the effectiveness of control. In these trials it was determined that the maximized desired system displacement was at 0.007 meters. To confirm this value for the optimal control several cost functions were evaluated. The normalized time history of the displacement is minimized at the expected at 0.007 meters.

$$JC_1 = \frac{\max(disp_{controlled})}{\max(disp_{uncontrolled})}$$

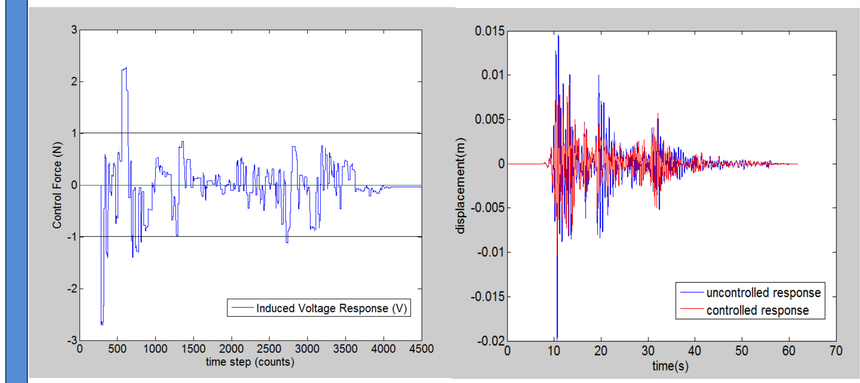
$$JC_3 = \frac{\max(acc_{controlled})}{\max(acc_{uncontrolled})}$$

$$JC_2 = \frac{||disp_{controlled}||}{||disp_{uncontrolled}||}$$

$$JC_4 = \frac{||acc_{controlled}||}{||acc_{uncontrolled}||}$$



Using this response, the bio-inspired control algorithm was executed using Newmark's Method. In simulation, the bio-inspired node transmitted displacement data which was then weighted by the associated LQR coefficients to obtain a control force, which was applied as a counter-acting force to the structure's response. These results show great promise for implementing control in the shear structure system.



Future Work

1.) Run physical trials to determine the full extent to which control is implemented
2.) Test results against other control implemented using traditional wireless sensors
3.) Scale up to a larger, 4 story, shear structure and investigate control

Acknowledgements

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